Modelling of Residual stress as a function of temperature in EDM

Thesis submitted in partial fulfilment of the requirements for the Degree of

BACHELOR OF TECHNOLOGY (B. TECH.)

IN

MECHANICAL ENGINEERING

BY

ASHUTOSH SUBUDHI

ROLL NO. 110ME0334

UNDER THE GUIDANCE OF

PROF. SOUMYA GANGOPADHYAY

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA 769008, INDIA
National Institute of Technology

ROURKELA

CERTIFICATE

This is to certify that the thesis entitled, "**Modelling of Residual Stress as a function of temperature in EDM**" submitted by **Sri Ashutosh Subudhi** in partial fulfilment of the requirements for the award of **Bachelor of Technology in Mechanical Engineering at the National Institute of Technology, Rourkela** (Deemed University) is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embroiled in the thesis has not been submitted to any other University/ Institute for the award of any Degree or Diploma.

Dr. Soumya Gangopadhyay
Assistant Professor

Department of Mechanical Engineering

National Institute of Technology, Rourkela

ROURKELA-769008

DATE:

ACKNOWLEDGEMENT

I deem it a privilege to have been one of the students of Mechanical Engineering stream in National Institute of Technology, ROURKELA.

My heartfelt thanks to Prof S. Gangopadhyay, my supervisor, whose invaluable encouragement, suggestions, and support led to make successful completion of the thesis work. His meticulous guidance at each phase of this thesis has inspired and helped me innumerable ways. I am feeling felicitous in deep of my heart to work under such a young, dynamic, intelligent professor and his excellence of supervision, which helped me to bring out this project in good manner with his precious suggestion and rich experience.

I take this opportunity to express my sincere thanks to my project guide for co-operation and to reach a satisfactory conclusion.

ASHUTOSH SUBUDHI

ROLL NO : 110ME0334

Abstract

Innovative developments have prompted an expanding utilization of high quality, high hardness materials in manufacturing industries. While machining of these materials, conventional manufacturing methods are progressively being supplanted by more exceptional strategies, for example, electro-discharge machining (EDM), electric chemical machining (ECM) ,ultrasonic machining (USM), and laser machining. EDM displaces materials by dissolving and vaporizing brought about by the high heat inside the discharging column.

EDM includes the complex involvement of numerous physical phenomena. Electric spark between the cathode and anode produces a lot of heat over a little region of the work-piece.

This work is intended on analysing the residual stresses caused in EDM process as a function of temperature. A model based on the Stablein's relationship/equation is found, which is a relationship of residual stress with respect to depth of the workpiece. Then a model is proposed of depth as a function of temperature. Through the statistical analysis an empirical relation is found between the latter and it is used in the former equation.

CONTENTS

Nomenclature

T is the temperature(in K)

r is the radial axis (in m)

z is the vertical axis (m)

t is time (s)

α thermal diffusivity of material (m^2/s)

K_t is the thermal conductivity of material (J/mK s)

ρ is the material density (kg/m^3)

C_p is the specific heat (J/kg K)

m latent heat of melting (kJ/kg)

T_m is the melting temperature (K)

S surface, for surface integral

σ_{rr}, σ_{qq} , σ_{zz} stresses in the normal directions

σ_{rz} shear stress

ε_{rr}, ε_{qq} and ε_{zz} strains in the normal directions

ε_{rz} shear strain

u and w displacements in those directions

ΔT temperature rise

E young's modulus

ν Poisson's ratio

α_t coefficient of thermal expansion

δ removal depth

H initial sample thickness

E_t is total energy supplied

I_{av} ,I is average discharge current

U_{av} average voltage

t_p pulse time

R_w energy partition to the cathode, i.e. the fraction of energy going to cathode

1. Introduction

EDM is a non-traditional manufacturing and a stand-out amongst the most prominent material removal methods on the basis of material evacuation from a metallic (generally solidified and hardened surfaces) part by electric discharges between the tool and the work piece in the vicinity of a dielectric liquid. The dielectric liquid makes it conceivable to flush the dissolved particles (for the most part as emptied surfaces) from the crevices and it is extremely vital to keep up this flushing efficiently for the procedure to be done proficiently.

With the increasing usage of EDM, from a development to an exceptionally handy and beneficial procedure, its veracity is plainly shown in its various applications. The difficulties being confronted by the present day manufacturing businesses from the improvement materials, for example, carbides, ceramics, composites, stainless steels, super alloys, heat resistant steel, and so forth. These materials are generally utilized as a part die and mould making, also in commercial ventures like, aviation, aeronautics, and likewise in nuclear and atomic industries, owing to their high strength to weight ratio, the heat resistant qualities and the hardness.

EDM machining is done by the help of electric sparks which are created between tool and workpiece, when immersed in a dielectric liquid and subjected to a voltage. Subsequently, the voltage applied must be sufficient to make an electric field to overwhelm the dielectric rigidity of the liquid utilized within the procedure. As an outcome of this electric field, electrons and positive ions accelerate, transforming a discharge channel that turns into being conductive. At that moment when the spark jumps, collision is caused between both the particles and a channel of plasma is created. The sudden drop of electric resistance of the past channel permits the current density to reach a very high value producing increment in ionization and also the creation of a powerful magnetic field. These impacts make a small part of metal volume liquefy or even vaporize. Erosion by an electric release includes certain phenomena like heat conduction, melting, energy distribution evaporation, ionization, formation and collapse of gas bubbles in the discharge channel.

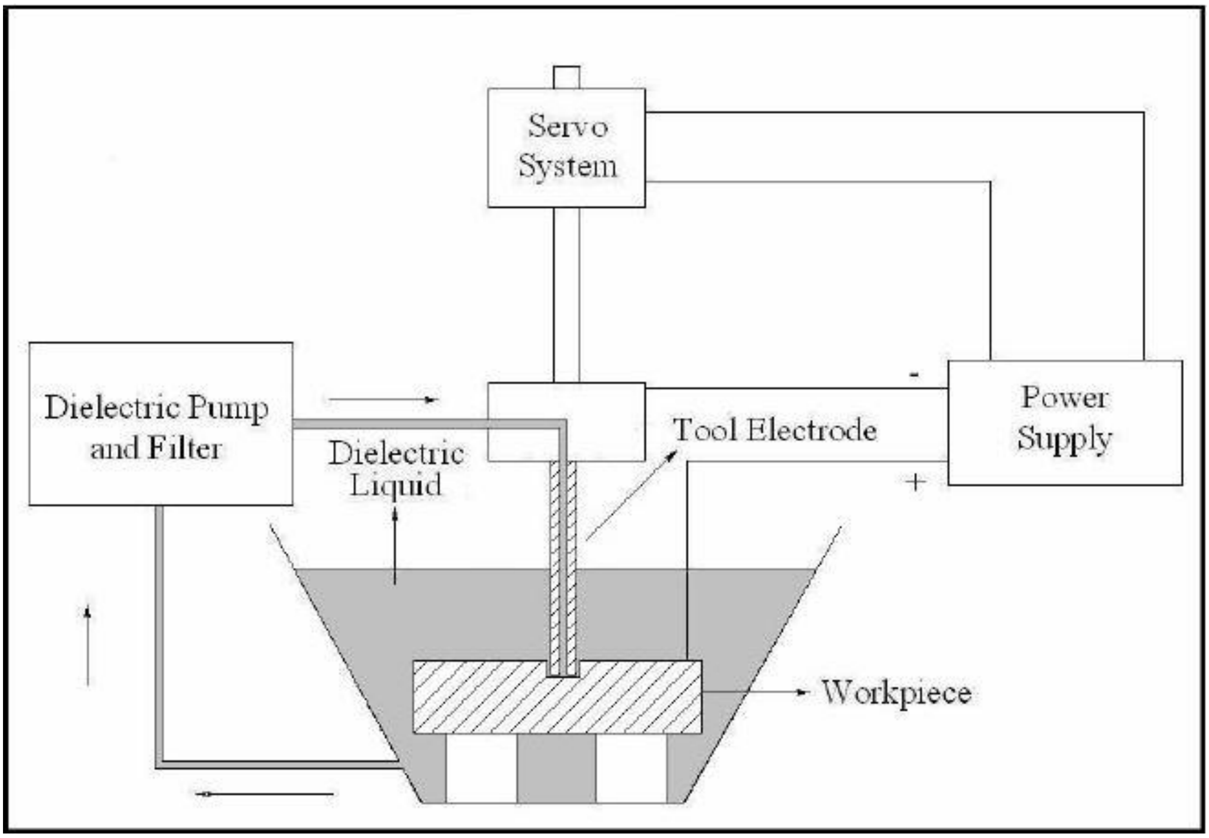

Figure 1 Basic Elements of an EDM System [6]

When seen from the viewpoint of machining vitality/energy, each one of the pulse throughout the discharge procedure is a yield of energy and the input discharge current together with discharge duration and moderately consistent voltage for a given tool and workpiece materials, represents amount of the energy for every pulse used in the spark gap region. The aggregate energy relies on upon the amount of sparks in each one second and the measure of energy in the sparks. The electrical energy supplied throughout this procedure is changed over into heat energy and this is conveyed around the different parts of the setup (workpiece, tool electrode and dielectric liquid) and is additionally imparted by countless methodologies happening throughout the fundamental stages (ignition, main discharge, melting, evaporation, and expulsion) of EDM methodology. The portion of the produced heat entering the terminal and the effective energy for removal, as indicated by a few examiners, relies on upon the warm properties thermal properties like density, melting point, thermal conductivity, specific heat and yield strength of the electrode, distance between electrodes, discharge current and discharge on time, conductivity of the dielectric and flushing pressure.

Henceforth, varied materials actually when machined, under same machining conditions might bring about distinctive machining qualities and subsequently a less accurate thermal models. The fraction/part of energy which is transferred to the workpiece, is a imperative parameter of thermal modelling, is to a great degree trouble to finish up and spot-on a succinct and distinct physical amount which can completely portray the properties of workpiece, and use it to anticipate the machinability. Different thermal models are proposed for electric discharge machining have indicated the stochastic nature and the complexities of various releases provide challenges while examining the procedure theoretically.

The recast layer, [20], additionally alluded as white layer as it's very difficult to etch and has an appearance under optical microscope which seems white. Underneath recast layer, a high temperature influenced region is structured because of fast heating and quenching cycles throughout the EDM .The nature of a EDMed material is generally assessed as far as its surface integrity, described by the presence of surface cracks, surface roughness and residual stresses.

There are two different types of Electro Discharge Machining:

1)Die-sinking 2) wire-cut

Die-sinking electrical discharge machining replicates the whole shape and structure of the tool utilized (electrode) and in the part wire-cut EDM, metal wire is utilized to have a programmed cut-out on the workpiece. Regardless of the favourable circumstances that present EDM processes, a stand-out amongst the most imperative impediments is the long manufacturing time.

The noncontact machining technique of EDM, is being diversified everyday by new methods. Since discovery of EDM nearly 60 years ago by Russian scientist Lazarenkos, also a young researcher Zolotykh, the improvements and researches of the process are still in progress to reinforce the ability of this process by pinpointing the basic physical processes involved during the process and hence a quantitative theory of the mechanism of material removal by the spark erosion is yet to be extensively formulated. For the some years, extensive research is being taken place in the field of thermal modelling for precise prediction of machining parameters, for example surface roughness, MRR , but still there is no proper model explaining in details the different processes which take place during a discharge in electro discharge machining process.

It is by and large acknowledged that displaying of discharge in EDM is essentially a thermal erosion procedure, [1] where the heat transfer happens. In this manner various streamlined thermo-mathematical models focused around the comparisons of heat conduction equations through solids. Craters' shape is formed, it's depth, MRR and surface roughness could be evaluated from these models.

2. Literature Review

2.1 *Theoretical models in EDM*

2.1.1 Modelling of heat sources in EDM

Most of the models use the Fourier heat conduction equation as the governing equation with the suitable boundary conditions. The equation is given as below;

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial Z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

…………..(1)

α can be written as:

$$\alpha = \frac{K_t}{\rho C_p}$$

Thermal diffusivity, if melting heat is also considered can be shown as:

$$\alpha' = \frac{K_t}{\rho(C_p + m/T_m)}$$

Different heat source models are given as:

2.1.1.1 Plane heat source

If the source of heat is assumed to have infinitely long radius, heat flow statement can be summarised to a single-dimension problem. Solution to the equation (1) is, as given in [1]:

$$T(t) = \frac{(c\gamma)^{1/2}}{8(\pi k)^{3/2}} \int_s \mathrm{d}S \int_0^t Qt(t-\tau)^{-3/2} \exp\left[-\frac{r^2}{4a^2(t-\tau)}\right] \mathrm{d}\tau$$

……(1a)

2.1.1.2 ***Circular heat source***

If radius of the source of heat is thought to have a finite value then the source of heat can be considered as a circular heat source. Harminder; Zingerman [1] and Harminder; Zolotykh [1] utilized this model and found a close relation between theoretical and experimental results. Harminder [1] proposed the solution of Eq. (1) as, for a circular heat source:

$$T(t) = \frac{(c\gamma)^{1/2}}{8(\pi k)^{3/2}} \int_0^b x\mathrm{d}x \int_0^t Qt(t-\tau)^{-3/2} exp\left[-\frac{h^2 + x^2}{4a^2(t-\tau)}\right] \mathrm{d}\tau$$

…….(1b)

2.1.1.3 ***Point heat source***

The plasma channel diameter and the source radius are taken to be small for small discharge durations and the heat source is assumed to be an instantaneous point heat source. In Harminder- Zingerman [1], the solution of equation (1) can be given as:

$$T(r,t) = \frac{c\gamma}{8(\pi k)^{3/2}} \int_0^t Qt(t-\tau)^{-3/2} \exp\left[-\frac{r^2}{4a^2(t-\tau)}\right] \mathrm{d}\tau$$

………(1c)

2.1.2 Thermal stress model

The extreme temperature gradients which occur during electrical discharge machining, as discussed in [19], results in very large non uniformities during the thermal expansion of workpiece material locally,(known as strain) which leads to very large thermal stresses. Temperature distribution in workpiece which is transient can be obtained by solving the equation of heat conduction also with initial and boundary conditions which are used as input to calculation of the thermal stresses. Basic equations for the axisymmetric thermal stress models are:

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{\partial \sigma_{rz}}{\partial z} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} = 0$$

………………(2)

$$\frac{\partial \sigma_{rz}}{\partial r} + \frac{\partial \sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r} = 0$$

……………………..(3)

Here body forces and the initial forces are negleted. Strain and displacement relations are as follows:

$$\varepsilon_{rr} = \frac{\partial u}{\partial r}, \varepsilon_{\theta\theta} = \frac{\bar{u}}{r}, \varepsilon_{zz} = \frac{\partial w}{\partial z}, \varepsilon_{rz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r}$$

…………….(4)

The strain-stress relationship due to rise in temperature can be written as:

$\{\sigma\} = [D]\{\varepsilon\}-\{m\}$

where [D] is the elasticity matrix, $\{\sigma\}$ is the stress vector and $\{\varepsilon\}$ is the strain vector. Expressions for them are as follows:

$\{\sigma\}^T=\{\sigma_{rr}, \sigma_{\Theta\Theta}, \sigma_{zz}, \sigma_{rz}\}$

$$\{\varepsilon\}^T = \{\varepsilon_{rr}, \varepsilon_{\Theta\Theta}, \varepsilon_{zz}, \varepsilon_{rz}\}$$

$$\{m\} = \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{Bmatrix} (E\alpha_t \Delta T / (1-2\nu)$$

$$[D] = \left(E/(1+\nu)(1-2\nu) \right) \begin{pmatrix} (1-\nu) & \nu & \nu & 0 \\ \nu & (1-\nu) & \nu & 0 \\ \nu & \nu & (1-\nu) & 0 \\ 0 & 0 & 0 & (1-2\nu)/2 \end{pmatrix}$$

2.2Electrical Discharge Machined surface integrity

2.2.1 Metallurgical characteristics of the EDM’ed surface

[21] The structural progressions of electro discharge machined surfaces were studied. For the tool steels, it is demonstrated, from different examiners, the upper-most layer of the surface is a non-etchable layer and uneven, specifically called the 'white layer'. It is a re-cast layer structured by the molten metal getting solidified at a very high rate after the discharge procedure is finished. Underneath the 'white layer' there is a halfway intermediate layer, a high temperature-influenced region, where heat is not sufficiently high enough to cause melting however it is high enough to affect the micro-structural changes in the material. Re-cast layer was found to be intensely alloyed with pyrolysis remnants of the cracked dielectric material. When the tool electrode, let's take copper, for instance, is perfectly compatible, surface alloying can be likewise found. Along with the compatible reagents, it is shown that, contingent upon the machinability conditions and on the steel, a diverse micro-structures of it, can come about.

Many an authors have described that the spark-affected layer could be different if they were machined by copper or graphite electrodes; dendritic austenite and a cementite–austenite eutectic or a fully austenitic surface followed by an austenite–cementite matrix, respectively. Same structure of carbides in the austenitic matrix have been described by some other authors, but it was stated that for a variety of electrodes it would not change the structure of white layer but the ratio of the carbide and the austenitic phases would vary. Increase in carbon content in the sub-surface layers and surface layers as a result of electro discharge machining has been pointed out by many a researchers to the pyrolysis of dielectric, and others have suggested that the carbon is assimilated more rapidly from the graphite electrodes than from the carbonaceous dielectric.

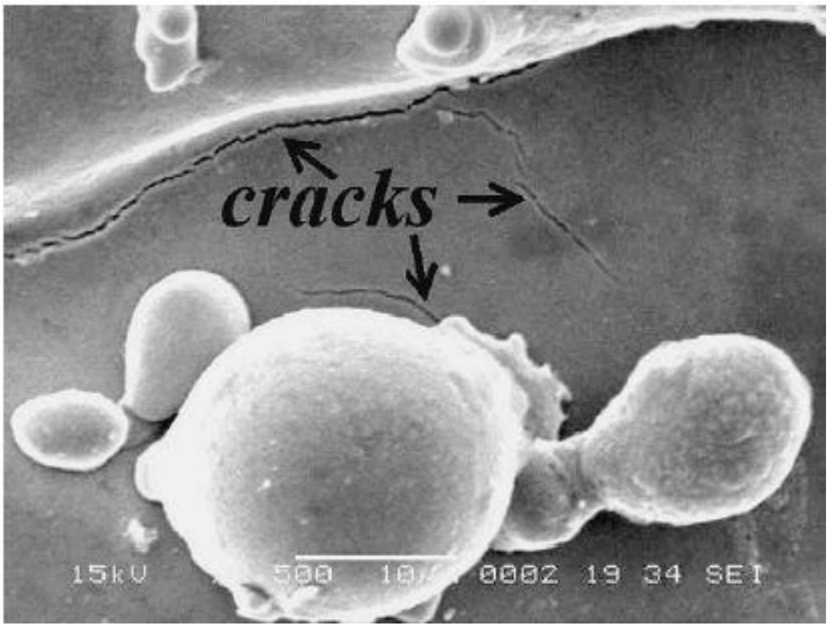

Figure 2 Micro crack formation on EDM sample [20]

Residual stresses are generated in EDM, due to metallurgical transformations and non-homogeneity of the heat flow. Research for the residual stresses of EDMed surfaces has revealed the tensile behaviour, and their high values at the surface layers, the narrowness of the superficial zone where they appear, and the increment of their value with the increment of pulse energy.

[20] A thick multi layer which is made up of two or three single layer type recast layers which overlap each other is formed as a result of the molten metal which oozes onto an existing recast layer and finally gets solidified. A very thin featureless layer can be very lightly identified on the surface and also between the overlapped recast layers. A relatively thick featureless layer which separates the base material and heat affected zone indicates that any coring effect in these layers is negligible. Also changes in depths of the featureless layers, suggests that molten metal is solidified at the centre of the melt where temperature gradient is much higher than on the surface. Voids were found to start from a point which was on the interfacial line of the overlapped recast layers. Also tiny amount of gas was trapped under the ridges of the craters by the action of expelled molten material while the discharging process took place. This gas that was trapped would formulate a bubble and

would expand until it instantly freezes due to the high cooling rates during solidification process.

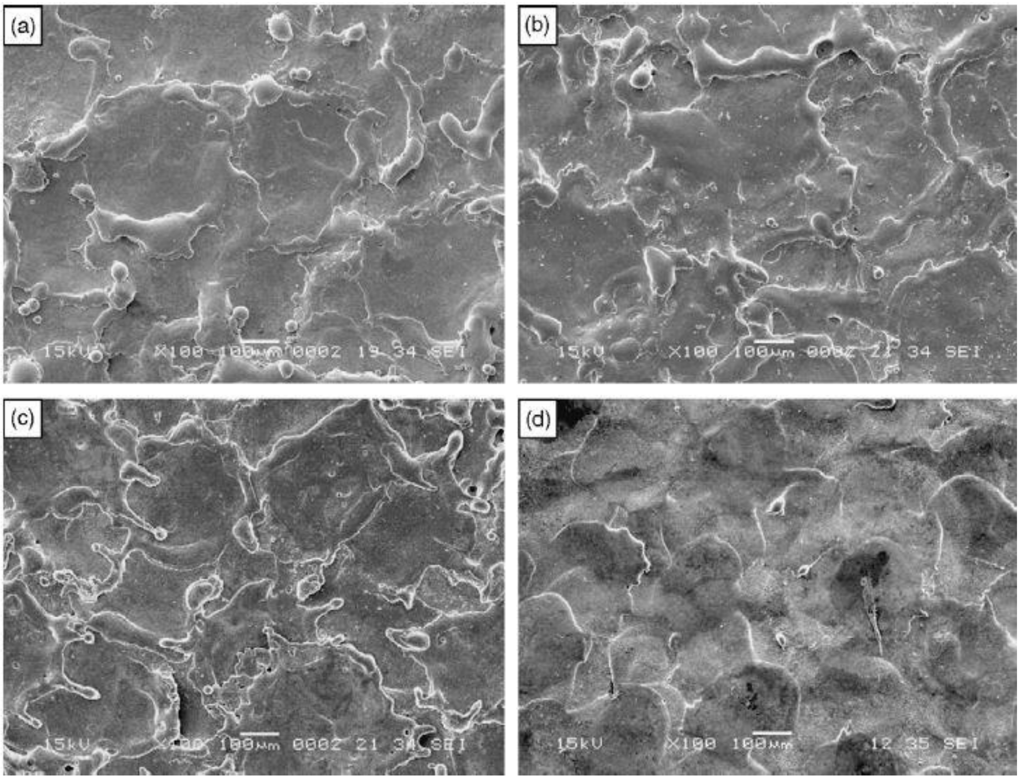

Figure 3 SEM micrographs of EDMed surfaces [20]

2.2.2 Residual stresses and Thermal Stresses

[4] These are self-equilibrating stresses that exist in structures under the uniform temperature conditions without any foreign loads. These stresses are produced if the regions of structures are non-homogeneous and plastically deformed in a permanent manner such that the strain incompatibilities would occur. Residual stresses are classified into three categories as per the distance over where they are equilibrated. They are the residual stresses of the 1st, 2nd and 3rd kind.

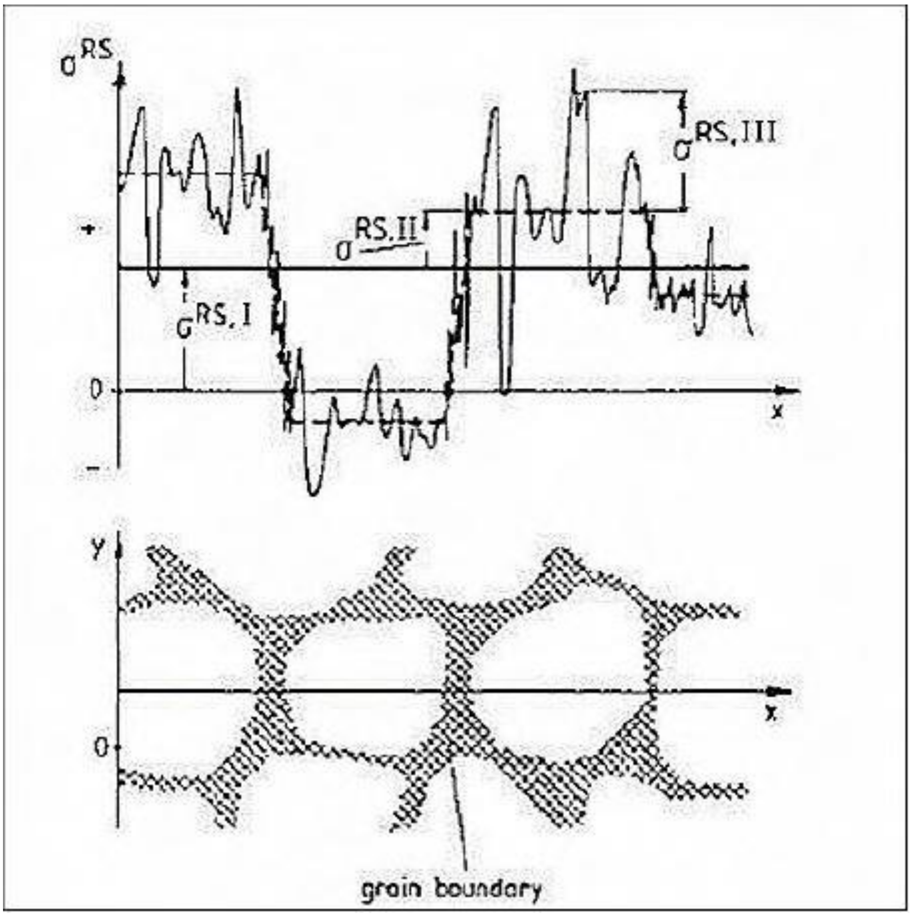

Figure 4 Illustration of a Stress State Composed of 1st, 2nd and 3rd Kind of Residual stress [4]

1st kind of the residual stresses are mostly homogeneous across large areas. For example the large area would comprise of some grains of the material and which are equilibrated inside the whole body. These stresses are also known as macro residual stresses. Now, residual stresses, the 2nd kind, are mostly homogeneous across the microscopic areas, which cover a distance of one grain or a part of the grain of a material and are equilibrated across a enough number of grains. These stresses are also called structural micro-stresses. The 3rd kind of residual stresses are inhomogeneous across the sub-microscopic areas of the material that would cover only some atomic distances along a grain and are equilibrated across the tiny part of the grain. These stresses are also called as micro residual stresses. The juxtaposition of all the three kinds would sum up the total residual stress state harnessed at a particular point for the structure [4].

For knowing the behaviour of the stresses , knowledge on the thermo-mechanical behaviour of the material is required, also the external forces to which the material is submitted, the interactions between the mechanical and thermal forces, and the structural transformations of the metal. Different properties and interactions have much importance .Figure 5 shows it and also they will depend on the type of treatment they undertake. Interactions can be explained as;

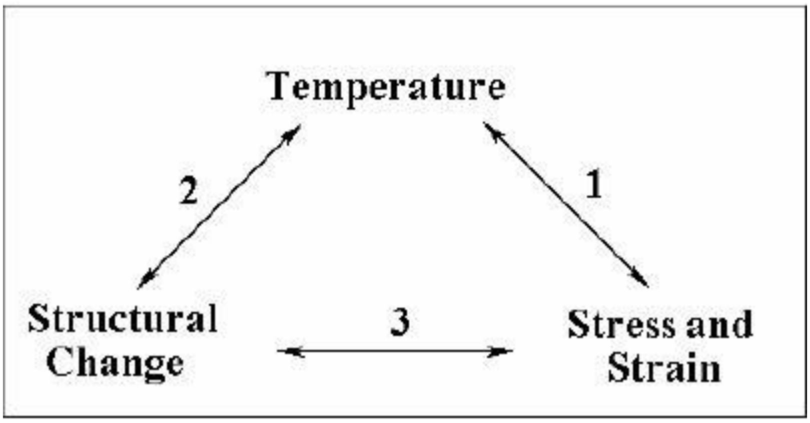

Figure 5 Data and Interactions for Predicting Residual Stresses [4]

For finding the internal stresses in a part, it is essential to know the external forces [4]. These forces may be:

(i) Temperature gradients in the part

(ii) The chemical composition gradients

(iii) The deformation gradients

The most practical and most universal method of establishing the evaluation of temperature in a part is by solving the heat equation. It may not be possible to measure the residual stresses directly [4], but they can be analysed;

(i) From microscopic strains, which gets released, while part of the stressed material is removed from the body. This is the basis of all mechanical methods exclusively investigating residual stresses by 1st kind and 2nd kind.

(ii) From lattice strain, where the diffraction techniques are used to find the stressed lattice spacing.

(iii) From propagation velocities of birefringence of ultrasonic waves influenced by the residual stresses
(iv) From the magnetic properties and phenomena of the material that is influenced by all kinds of residual stresses.

The most useful mechanical techniques are as follows,
(i) Hole drilling method
(ii) Ring core technique
(iii) Layer method
(iv) Sectioning method

For the residual stress determinations the hole drilling or the ring core method are used, where strains in the vicinity of the hole due to semi release of residual stresses will be identified. And from those values and by usage of Poisson's ratio and Young's modulus and also the calibration coefficients of the material, the residual stresses can be measured by applying strain gauge configurations.

The concept behind layer removal method is the balancing of internal moments and stresses when the residual stresses are slowly relaxed from the material by subsequent thin layers using chemical machining or ECM. Resultant strains and deflections due to equilibrium of internal stresses are calculated to find residual stresses from the elasticity theory. In general, residual stresses in the outermost surface layers of the components cannot be measured easily.

If the sectioning technique is used, the equilibrium conditions for stresses and moments will be considered. The object is cut in section and the stress is relaxed. The averaged strain values are identified as per the bulk of the removed material, which determines the bulk of stress that is released. Residual stress values are analysed by any mechanical method can be contradicted with plasticity effects when very high quantities of stress would exist. Strong residual stress gradients and improper sectioning underneath the surface also may lead to some uncertainties in the results.

3. Modelling and formulation

Initially a model of residual stress with respect to depth was found out from the [4] paper. Aim of the present work is to find the residual stress as a function of temperature and this is done later by formulating depth as a function of temperature.

Residual stress and Depth

All the nomenclatures have been adopted from the papers [4,6].

Removing the stressed layers, theoretically, from a beam shaped component would result in bending or deflection because of formation of the new equilibrium state. Removal of each layer is followed by deflection which is expected to form a second order polynomial curve. Measured deflections and the corresponding second order polynomials for a EDMed surface after removal of each layer has shown very good agreement with the results expected. The curvature can be easily found from the given equation where $P_i(x)$ is the second-order polynomial which has a coefficient d which represents the deflection curve with compared to the sample length x after the removal of the i^{th} layer corresponding to removal depth (δ):

$$P_i(x)= d_i\,(x^2)$$

The curvature, $C(\delta)$, for a removal depth, δ , can be easily found by using the following equation:

$$C(\delta)=1/\rho(\delta) = \delta^2 P_i(x)/\,\delta^2(x) = 2d_i$$

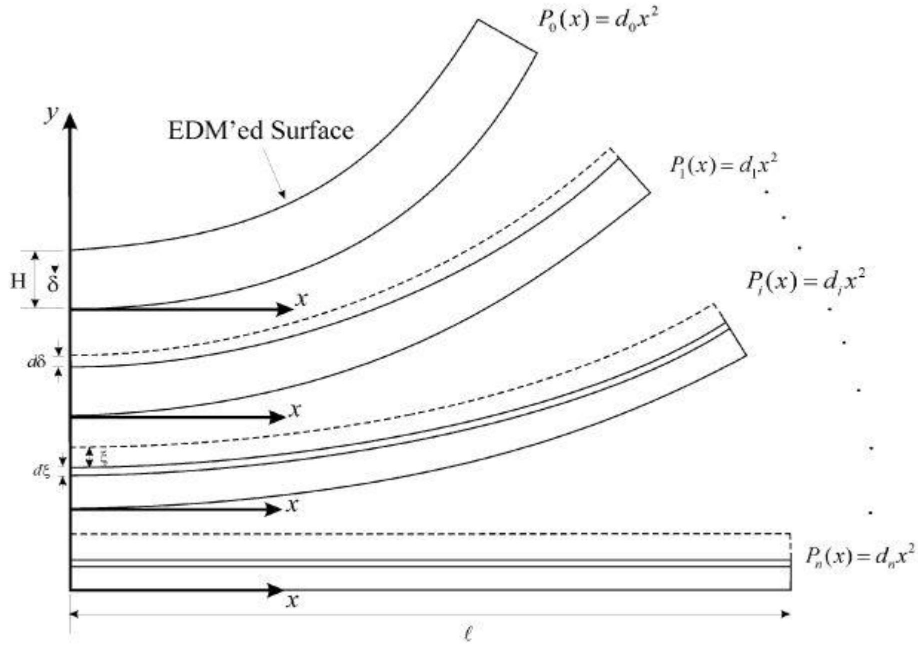

Figure 6 Deflection of sample due to layer removal [6]

To find the curvature, the ratio of the measured average removed layer depth, δ, to the initial sample depth or thickness, H, is defined as dimensionless thickness δ^*, and a dimensionless curvature $C^*(\delta)$, which is represented as;

$$\delta^* = \delta/H$$

and,

$$C^*(\delta) = H.\, C(\delta)$$

The dependence of the variables, relationally is found as a special form of Gaussian distribution, which is the sum of two Gaussian peaks, with the same amplitude and the pulse width but with opposite center location. Relation can be expressed in the following form:

$$C^*(\delta) = a_1 \cosh(a_2\delta^*) \exp(-(a_3\delta^*)^2)$$

a_1, a_2 and a_3 are found from empirical relations [4,6] and there values are given as 0.0003653, 53.33, and 43.89 respectively.

Aggregate energy supplied for a single spark can be written as:

$$E_t=I_{av}U_{av}t_p$$

It would be more realistic to use the aggregate energy received by the workpiece during machining. But, many a investigators have assumed that some constant fraction of total power is goes to electrodes. The energy fraction to cathode be R_w, which is usually taken as 0.08. So, the total amount of energy harnessed by the workpiece due to single discharge can be shown as:

$$E_w = R_w I_{av} U_{av} t_p$$

Thermo-physical properties of the material should also be included, hence E_w becomes E_w*, which is dimensionless and it is given as;

$$E_w^* = E_w \left[(\rho^5 c^9)/(k^8 \alpha)\right]^{1/3}$$

A new parameter g*is defined in order to scale the constant coefficients a_1, a_2, and a_3. Henceforth we can obtain the coefficients for different pulse energies by using g*.Hence scaling factor g* which is dimensionless is found to be dependent on the dimensionless energy for a single spark as follows:

$$g^*=204.5*10^{-6} (E_w^*)^{0.38}$$

Finally the generalized and proposed form of curvature dependent on a_1, a_2,
a_3, and g* can be expressed as:

$$C^*(\delta)=A_1\cosh(A_2\delta^*)\exp(-(A_3\delta^*)^2)$$

Where $A_1=a_1g^*$, $A_2=a_2/g^*$ and $A_3=a_3/g^*$.

And now, when the proposed empirical relation is inserted into the dimensionless form of Stablein equation [4,6] we have;

$$\begin{aligned}\frac{\sigma_p^{rs}(\delta^*)}{\mathrm{E}} &= \frac{(1-\delta^*)^2}{6}A_1\cosh(A_2\delta^*)\exp(-A_3^2\delta^{*2}) \\ &\times\left\{2A_3^2\delta^* + \frac{4}{(1-\delta^*)} - A_2\tanh(A_2\delta^*)\right\} \\ &+\frac{(3\delta^*-2)}{3}A_1 - \frac{\sqrt{\pi}}{12}\frac{A_1}{A_3}\exp\left(-\frac{A_2^2}{4A_3^2}\right) \\ &\times\left\{erf\left(\delta^*A_3-\frac{A_2}{2A_3}\right)+erf\left(\delta^*A_3+\frac{A_2}{2A_3}\right)\right\}\end{aligned} \quad \text{.......(5)}$$

The result is the residual stress profile as a function of depth caused by EDM. Constants A_1, A_2, and A_3 are the empirical coefficients found erstwhile.

Depth and temperature

Now, the proposed equation gives the residual stress profile with respect to depth. But the aim of finding residual stress with respect to temperature is still to be founded. The assumptions taken in the model given in [5] are;

- Model developed is for single spark
- Workpiece considered as a semi-infinite body
- Thermal effects of successive sparks on each other are neglected
- Phase changes are neglected during analysis
- Crater formed on workpiece due to each discharge is assumed to be circular parabolic

- Redeposit of recast layer in the crater after each spark is considered to be uniform.

Hence, now depth as a function of temperature is formulated from a data given in [5];

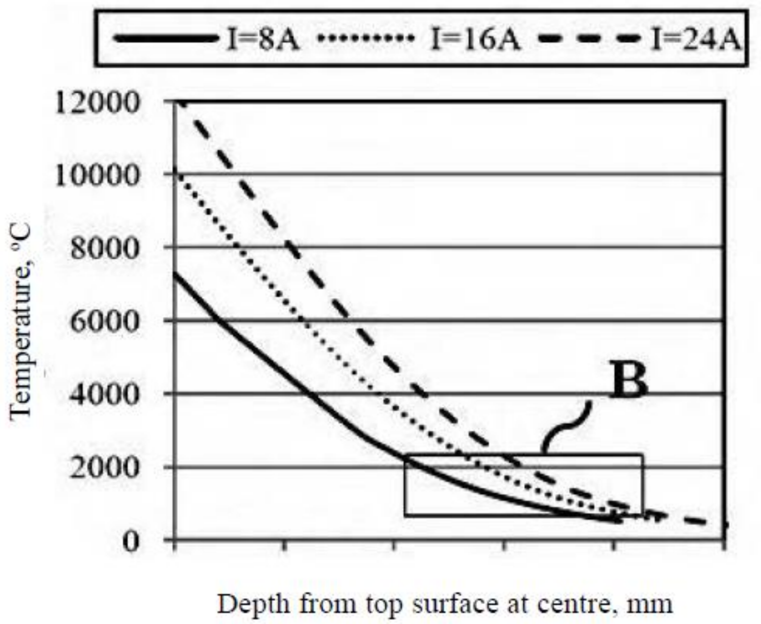

Figure 7 Temperature distribution along depth of workpiece at centreline discharge position [5]

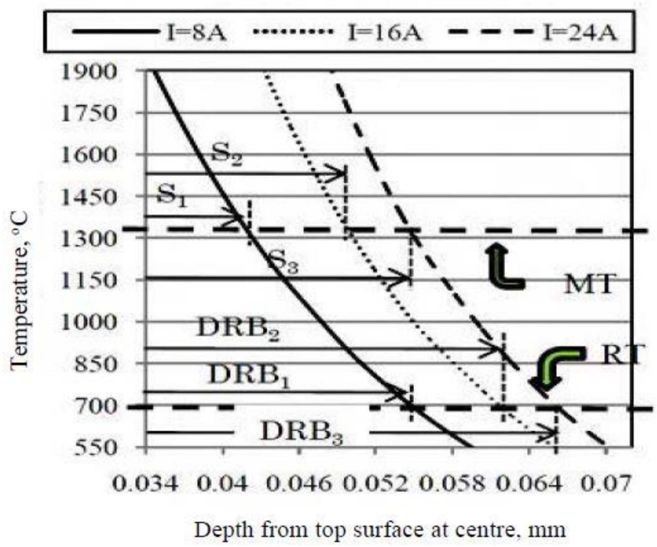

Figure 8 A zone in fig 5 from [5]

So, the data was extrapolated from the second graph (figure) and they are;

For I=24A we have,

Temperature (in ℃)	Depth from the top surface (in mm)
1900	0.049
1600	0.052
1450	0.054
1300	0.055
1150	0.0575
1000	0.06
850	0.0625
700	0.067
550	0.07

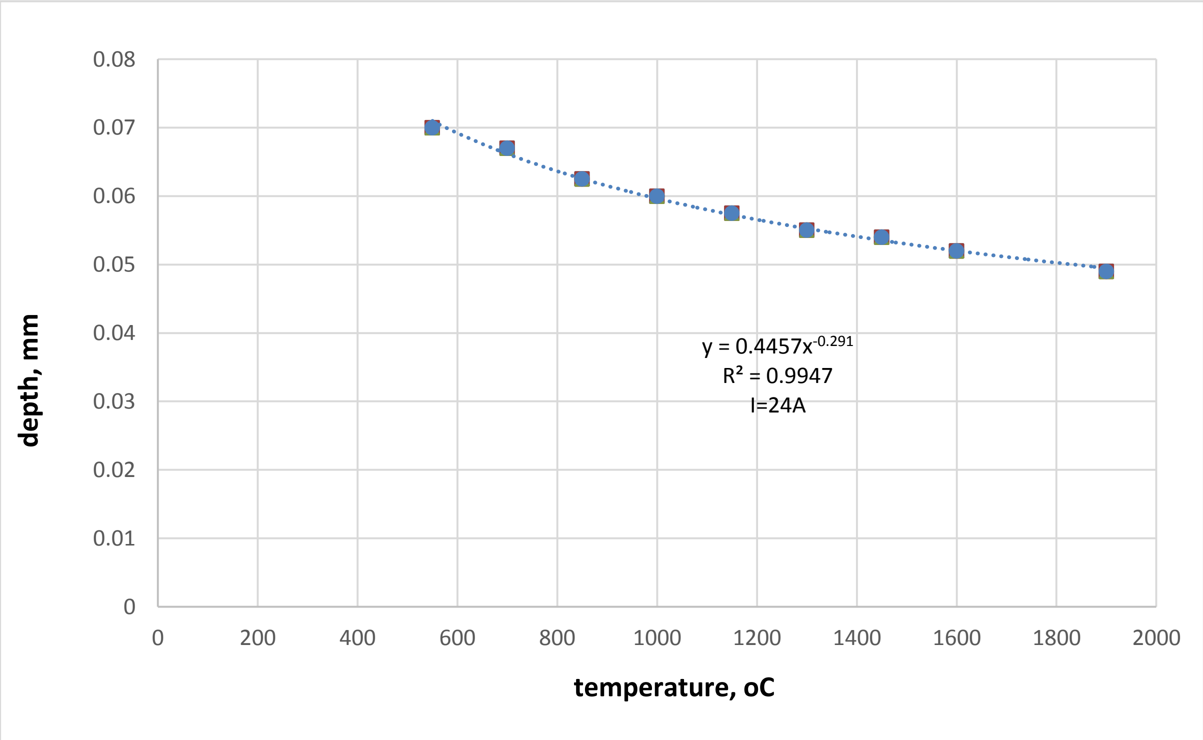

Figure 9 Graph between depth and temperature at I=24A

For I= 16A

Temperature (in ℃)	Depth from the top surface (in mm)
1900	0.044
1750	0.045
1600	0.047
1450	0.049
1300	0.0505
1150	0.052
1000	0.055
850	0.058
700	0.061
550	0.066

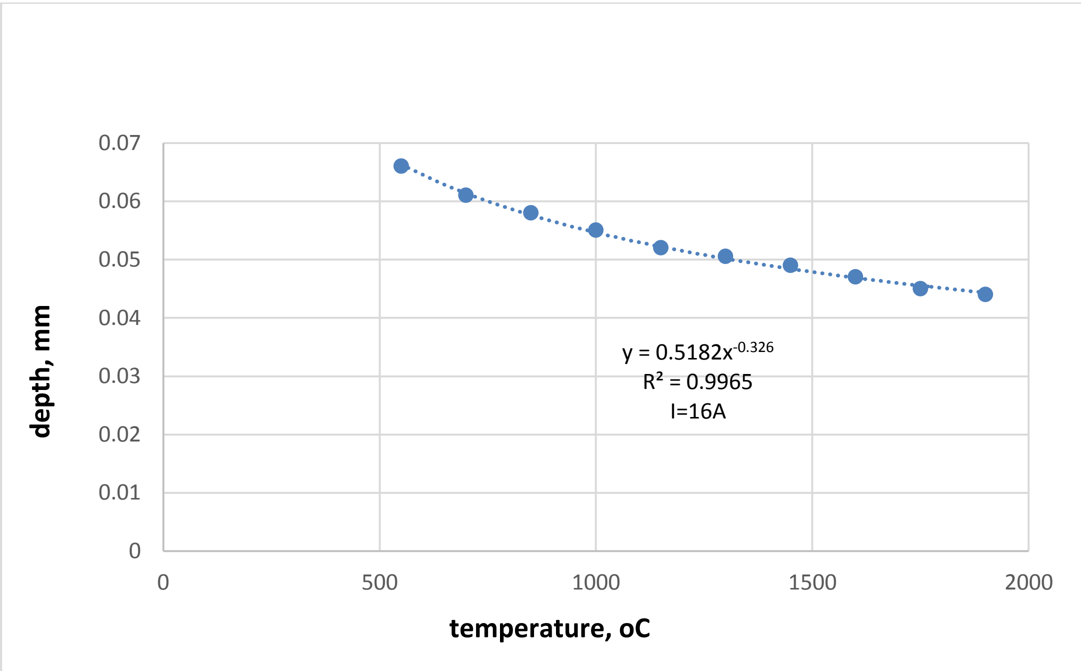

Figure 10 Graph between depth and temperature at I=16A

For I=8A, we have,

Temperature (in ℃)	Depth from the top surface (in mm)
1750	0.037
1600	0.0385
1450	0.04
1300	0.043
1150	0.0445
1000	0.048
850	0.0508
700	0.055
550	0.0595

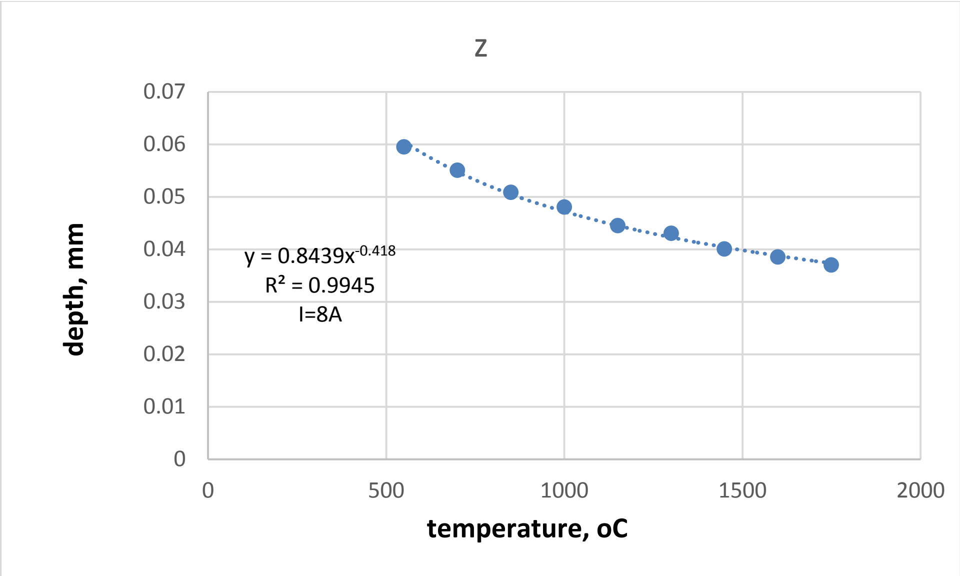

Figure 11 Graph between depth and temperature at I=8A

Hence, from the second graph where $R^2 = 0.9965$, we adopt the relation which is;

$$d= 0.5182t^{-0.326} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

t is temperature in Celsius and d is depth in mm.

Now this value of d or previously mentioned as δ is put in the Stablein's equation. So the new equation of residual stress profile with respect to temperature is;

$$\frac{\sigma rs(t)}{E} = \frac{(1-(0.5182t^{-0.326})*H)^2}{6} A_1 \cosh(A_2\,(0.5182t^{-0.326}) * H)$$

$$*\{\exp(-A_3^2\,(0.5182t^{-0.326})^2 * H^2)\}$$

$$*\{2A_3^2 * 0.5182t^{-0.326} + \frac{4}{1-(0.5182t^{-0.326})*H} - A_2 \tanh(A_2 * 0.5182t^{-0.326} * H)\}$$

$$+\{\frac{3*.05182t^{-0.326}*H-2}{3} A_1 - \frac{\sqrt{\Pi}}{12}\frac{A1}{A3}\exp(-\frac{A2^2}{4A3^2})$$

$$*\{\mathrm{erf}(0.5182t^{-0.326} * H * A_3 - \frac{A2}{2A3}) + \mathrm{erf}(0.5182t^{-0.326} * H * A_3 + \frac{A2}{2A3})\}$$

4. Validation of proposed relationship

The relationship between depth and temperature is validated by plotting a curve for another set of data [8].

Temperature, (in ℃)	Depth calculated ($d= 0.5182t^{-0.326}$),in mm, z	Depth extrapolated, in mm, z’
504.6	.0681	.072
727	.0604	.0586
837.96	.0577	.0536
1060.33	.0535	.051
1282.4	.0502	.047
1504.62	.0477	.045
1727	.0456	.041

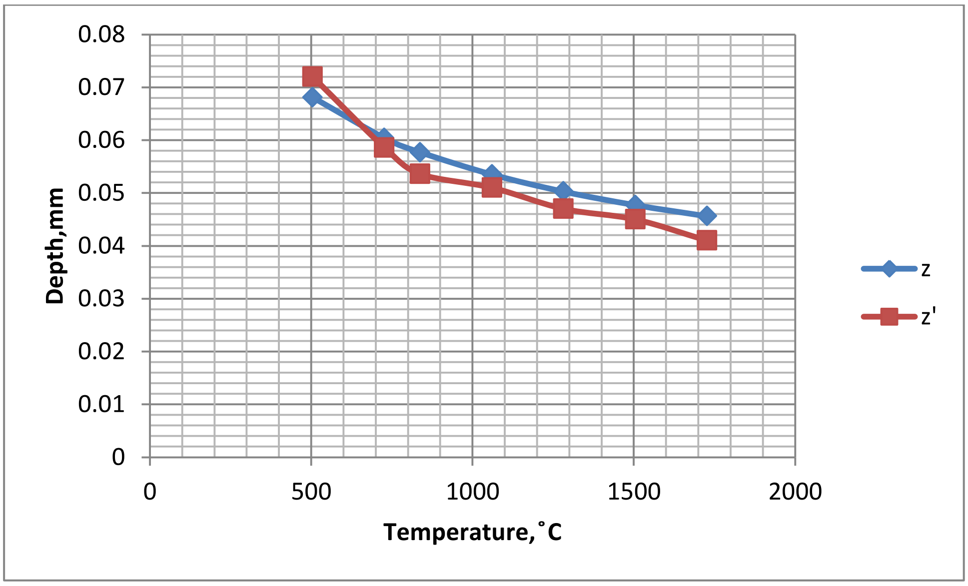

Figure 12 Validation of empirical relation

The graph shows the relational dependence of depth and temperature. Values of depth were calculated from the empirical relation, eq. (6). These values are very closely predicted with respect to the actual values found from extrapolation of the depth values in [8]. The blue curve is the empirical relation and the red one consists of actual values. Thus, most of the points almost coincide with each other. The difference occurs because the experimental conditions in the red curve are different from the one empirical relation was found. Value of current in it is 20A and T_{on} is 500 seconds. Hence, the little variations occur which are well under the tolerance limit. So, the empirical relation is validated with this new data.

Both the values are from simulated models, as actual experiment has not been carried out. Hence, a large amount of future scope is there in this regard, for validating the models experimentally.

5. Conclusion

The present work aims at establishing the relationship between temperature during EDM and the residual/ thermal stress generated. Following conclusions may be drawn from the current study:

1. Various thermal models have been studied in order to understand the correlation between depth of surface affected by EDM operation and the temperature and residual stress. The residual stress would rapidly increase compared to depth and reaches its maximum value within the heat-affected region.

2. The temperature has an exponential (empirical) relation with the depth. This relation is further used to connect the residual stress with the temperature and having the depth as an intermediate function which was eliminated later.

3. The graphs in figure 11,10 and 9 are compared extensively. The graph between depth and temperature for I=8A is the steepest and this implies that the value of temperature increases very rapidly with decrement of depth with respect to the other two curves.

4. The graph between depth and temperature for I=16A stays in between in the field of steepness. Also the curve for I=24A is the flattest and hence the temperature variation is not so rapid compared to other two.

5. So, it can be deduced as the average value of current increases the decrement of temperature with respect to depth is slower compared to the rate of decrement for lower values of current.

6. References

1. Harminder Singh, Experimental study of distribution of energy during EDM process for utilization in thermal models, International Journal of Heat and Mass Transfer, 2012
2. S. Hinduja, M. Kunieda; Modelling of ECM and EDM processes, CIRP Annals - Manufacturing Technology, 2013
3. PANKAJ KUMAR SONI,RAJU GHOLLEY; STUDY AND ANALYSIS OF RESIDUAL STRESSES IN ELECTRO-DISCHARGE MACHINING (EDM), E-thesis, NIT RKL, 2007
4. Bülent Ekmekci , Oktay Elkoca , A. Erman Tekkaya ,Abdulkadir Erden; RESIDUAL STRESS STATE AND HARDNESS DEPTH IN ELECTRIC DISCHARGE MACHINING: DE-IONIZED WATER AS DIELECTRIC LIQUID, Machining Science and Technology: An International Journal, 2005
5. M R Shabgard, A numerical method for predicting depth of heat affected zone in EDM process for AISI H13 tool steel, Journal of Scientific and Industrial Research, 2011
6. Bülent ekmekç, Theoretical and experimental investigation of residual stresses in electric discharge machining, a thesis submitted to the graduate school of natural and applied sciences of the middle east technical university, 2004
7. P. Shankar, V. K. Jain; Analysis of spark profiles during edm process, Machining Science and Technology: An International Journal, 2007
8. Mehrdad Hosseini Kalajahi, Experimental and finite element analysis of EDM process and investigation of material removal rate by response surface methodology, Int J Adv Manuf Technol (2013)
9. S. Keith Hargrove; Determining cutting parameters in wire EDM based on workpiece surface temperature distribution, Int J Adv Manuf Technol, 2007
10. E. Weingärtner, Modeling and simulation of electrical discharge machining, 1st CIRP Global Web Conference: Interdisciplinary Research in Production Engineering, 2012
11. Chinmaya P. Mohanty, Thermal-structural Analysis of Electrical Discharge Machining Process, Chemical, Civil and Mechanical Engineering Tracks of 3rd Nirma University International Conference on Engineering (NUiCONE 2012)
12. S.N. Joshi, S.S. Pande, Thermo-physical modeling of die-sinking EDM process, Journal of Manufacturing Processes, 2010

13. J.W. Murray, A.T. Clare, Repair of EDM induced surface cracks by pulsed electron beam irradiation, Journal of Materials Processing Technology, 2012
14. Shuvra Das , Mathias Klotz, EDM simulation: finite element-based calculation of deformation, microstructure and residual stresses, Journal of Materials Processing Technology, 2003
15. Y.H. Guu, Max Ti-Kuang Hou, Effect of machining parameters on surface textures in EDM of Fe-Mn-Al alloy, Materials Science and Engineering, 2007
16. Mohammadreza Shabgard, Mathematical and numerical modeling of the effect of input-parameters on the flushing efficiency of plasma channel in EDM process, International Journal of Machine Tools & Manufacture, 2012
17. Bu¨lent Ekmekci, A semi-empirical approach for residual stresses in electric
18. discharge machining (EDM), International Journal of Machine Tools & Manufacture, 2005
19. Vinod Yadav, Thermal stresses due to electrical discharge machining, International Journal of Machine Tools & Manufacture, 2002
20. Bu¨lent Ekmekci, Residual stresses and white layer in electric discharge machining (EDM), Applied Surface Science, 2007
21. J.C. Rebelo, Influence of EDM pulse energy on the surface integrity of martensitic steels, Journal of Materials Processing Technology, 1997